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5 Pollux Drive
Edwards AFB CA 93524-7048

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5 Pollux Drive
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MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 18 Sep 2001

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2001-190**
C.T. Liu, "Fracture Mechanics and Service Life Prediction"

AFOSR Program Review **(Statement A)**
(Washington, D.C., 18-20 Oct 2001) (Deadline: 05 Oct 2001)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
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APPROVED/APPROVED AS AMENDED/DISAPPROVED

PHILIP A. KESSEL Date
Technical Advisor
Space and Missile Propulsion Division

FRACTURE MECHANICS AND SERVICE LIFE PREDICTION RESEARCH

October 2001

C.T. Liu

Principal Research Engineer

PRSM

Air Force Research Laboratory

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Fracture Mechanics and Service Life Prediction Research

- **Objectives:**
  - Gain an Improvement in Understanding of Damage Mechanisms and Fracture Behavior in Solid Propellants and
  - Insulator/liner/ Propellant Bond System.
  - Develop Methods to Predict Crack Growth.
- **State of the Art:**
  - Deterministic Approach; Material Is Homogeneous; Crack Initiation Failure Criterion
- **Approaches:**
  - Experiments (Destructive and Nondestructive Tests);
  - Analytical Analysis and Numerical Modeling
- **Applications:**
  - Missile Systems(Titan IV; Minuteman; Air Launch Systems)

Pls capitalize the "l"

- pls delete this semicolon

Fracture Mechanics and Service Life Prediction Research

- **Uniqueness of Research:**
  - Unique Material (Dual Function Material)and Composite Structure.
  - Account for Microstructural Effect on Crack Growth Prediction.
  - Account for Local Behavior in Crack Growth Simulation.
  - Account for Time-Dependent Material Property and Property Gradient in Multi-Layered Structure.
  - Systematic Approach: Micro and Macro Measurement and Analyses.

Fracture Mechanics and Service Life Prediction Research

- **Past Years Accomplishments:**
  - Developed Rate-Dependent and Temperature-Dependent Probabilistic Crack Growth Models
  - Developed a Nonlinear Viscoelastic Constitutive Model and Incorporated It in a Finite Element Computer Code
  - Developed a Technique to Predict the Inherent Critical Initial Crack Size Under Different Loading Conditions
  - Determined the Effects of Microstructure on Damage Mechanisms and Strain Fields Near the Crack Tip
  - Developed a Technique to Determine the Effects of Residual Stress and Material Mismatch on Stress Intensity Factors at the Tip of Interfacial Cracks in Bi-material Specimens
  - Determined the Applicability of Using Homogeneous Continuum Approach to Analyze Solid Rocket Motors
- **Research Pay Off:**
  - Provide a Fundamental Understanding of Damage Mechanisms and Fracture Behavior in Solid Propellants and Insulator/liner/ Propellant Bond Systems
  - Provide Guidance for Developing High Strength Solid Propellants and Insulator/liner/ Propellant Bond Systems
  - Make Defect-tolerance Analysis Methodology Feasible.
- **Related Research Program:**
  - Fracture Mechanics Support (P.I. Dr. C. T. Liu; AFRL/PRSM)
  - Minuteman Support (P. I. Dr. C. T. Liu; AFRL/PRSM)
  - Service Life Prediction Technology (Program Manager Dr. G. Ruderman; AFRL/PRRM)
  - Critical Defect Assessment Program (Program Manager Dr. G. Ruderman; AFRL/PRRM)

CAP-UPPERCASE

PIs spell out "Principal Investigator"

he's in PRSB now

SB

SB

4 - PIs delete the period and add the back end of the parentheses.

Fracture Mechanics and Service Life Prediction Research

- **Application:**
  - The advanced service life prediction technology has been successively used to determine the service life of TITAN IV solid propellant grains and will be used to predict the service life of other missile systems.

Fracture Mechanics and Service Life Prediction Research

- **Success Story:**
  - Acceptance criteria have been developed and successfully used to determine the criticality of defects in Titan IV solid rocket motors. The total estimated savings to the Air Force are $100M.

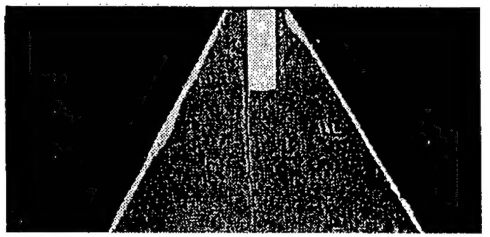
Fracture Mechanics and Service Life Prediction Research

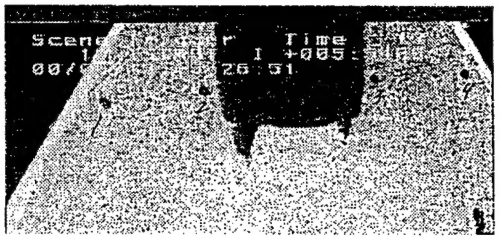
- **Significant Accomplishments:**
  - Developed a Time Independent Constitutive Model, Including Pressure Effect.
  - Determined Three-Dimensional Effect on Crack Growth Behavior.
  - Determined Load History Effect on Critical Damage Characteristics at the Crack Tip for the Onset of Crack Growth.
  - Determined Geometrical Effects on the Material Responses of Bi-material Bonded Specimens.

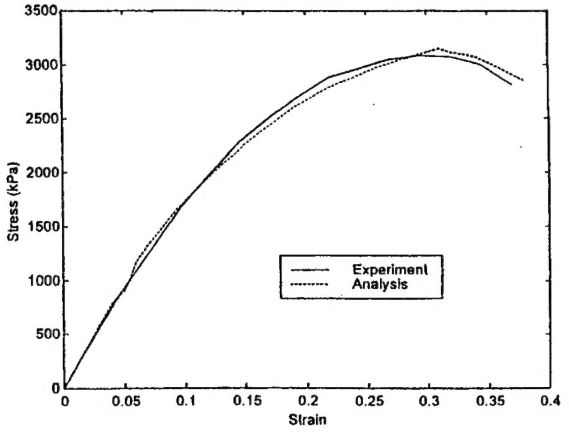
A1981.ppt

A Good Agreement Exists Between the Predicted and Measured Initial Crack Length in an Analogy Specimen

- A nonlinear constitutive model was developed which can be used to predict the stress-strain behavior under different confined pressure conditions.
- Under a constant displacement rate of 127 cm/min and 6896 Kpa confined pressure, the predicted initial crack length based on a micro-macro analysis, and the measured one are 1.70mm and 1.86mm, respectively.



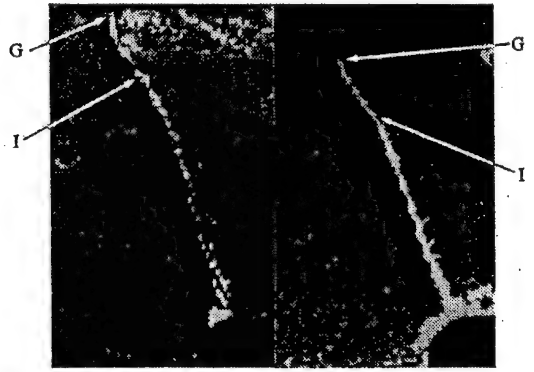




Comparison of Stress-Strain Curves with Hydrostatic Pressure (1000 psi)

A Significant Three-Dimensional Effect Occurs During Crack Turning

- After the crack turning process is completed, the crack grows under Mode I loading.
- Crack turning induces a significant reduction in crack growth rate.



Path of Cracks Midpoints when Blade is Normal to Fin Surface

I – initial crack tip location
G – crack tip location after growth

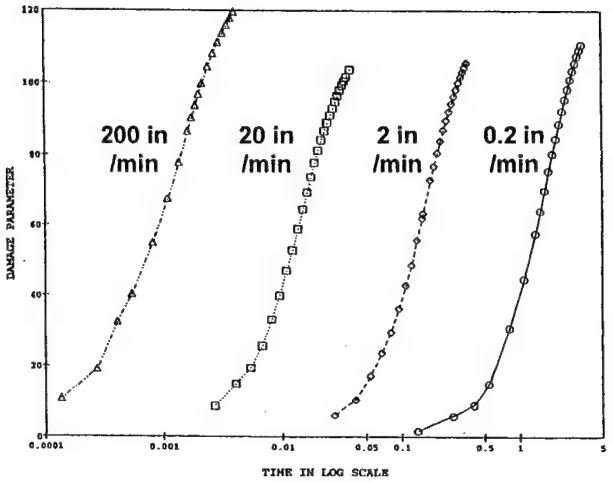
PHOTOELASTIC FRINGE PATTERNS

Crack Turning Completed

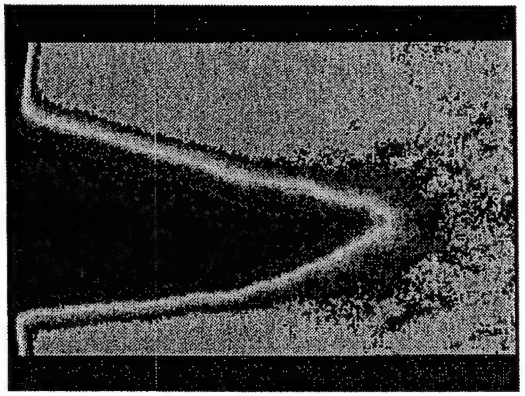
Crack Turning Incomplete

Load History Has No Significant Effect on the Critical Damage Characteristics at the Crack Tip for the Onset of Crack Growth

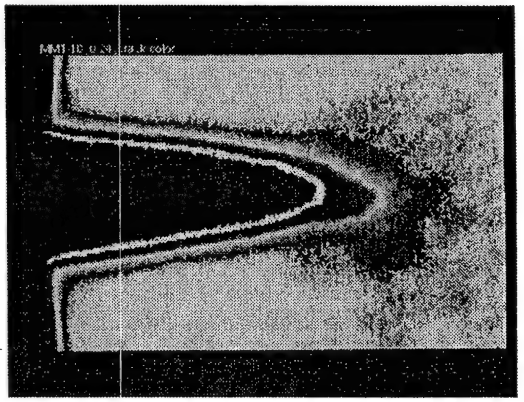
- The critical damage parameter, $N(t) = [\int_o^t \sigma^\beta dt]^{1/\beta}$, which is derived from a linear cumulative theory, is independent of the loading history.
- The critical x-ray intensities for the onset of crack growth in the virgin and pre-damaged specimens are 1806 and 2019, respectively.



X-RAY IMAGE



Pre-Damaged Specimen

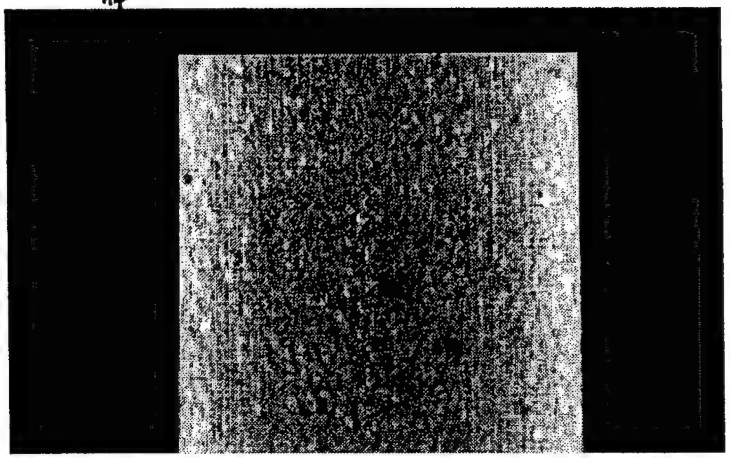


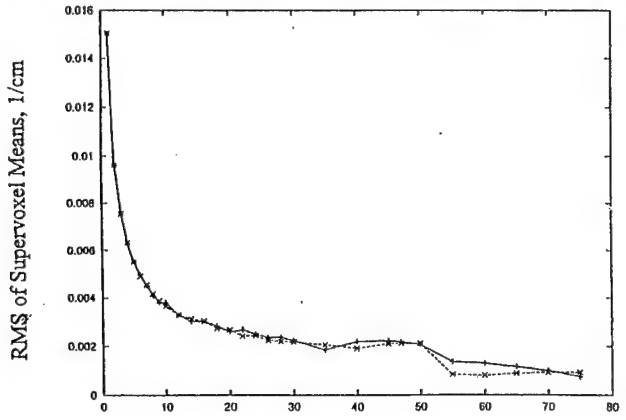
Virgin Specimen

There Exists a Representative Volume for a Valid Homogeneous Continuum Assumption of the Solid Propellant

if using a period in front of this "C" do so after the "T"

C.T. Image





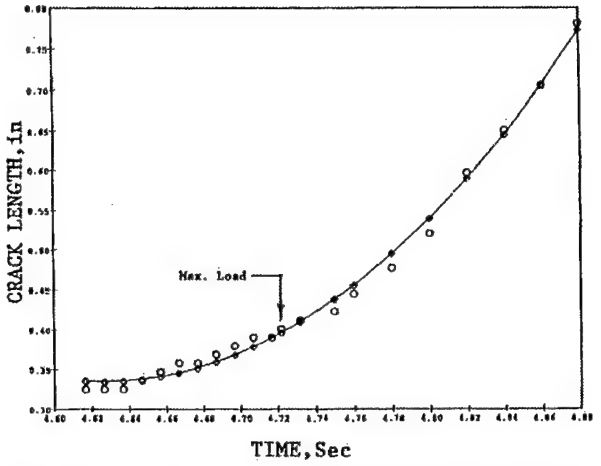
- Based on a computed-tomography analysis, the representative volume of the material studied is 2 mm x 2 mm x 2 mm.
- The computed-tomography technique is a promising technique to monitor damage initiation and evolution inside the specimen.

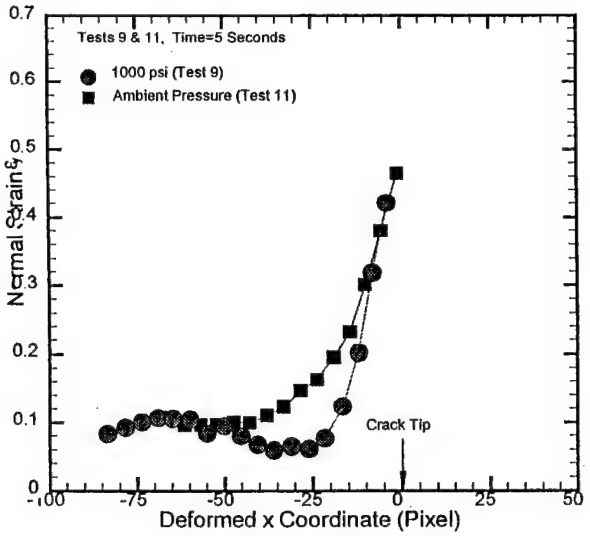
to use this word as a noun, it should be spelled "superimposition"

Under Constant Strain Rate Condition, the Superimpose of Confined Pressure Induces a Unique Crack Growth Behavior.

- Pls delete this period. (no periods w/ other headings)

- Crack Grows Slow.
  - Damage Initiation and Evolution Is Suppressed.
  - Strain Gradient, or Damage Gradient, Near the Crack Tip Is Increased.
- A Considerable Amount of Stable Crack Growth Occurs Beyond the Maximum Applied Load.





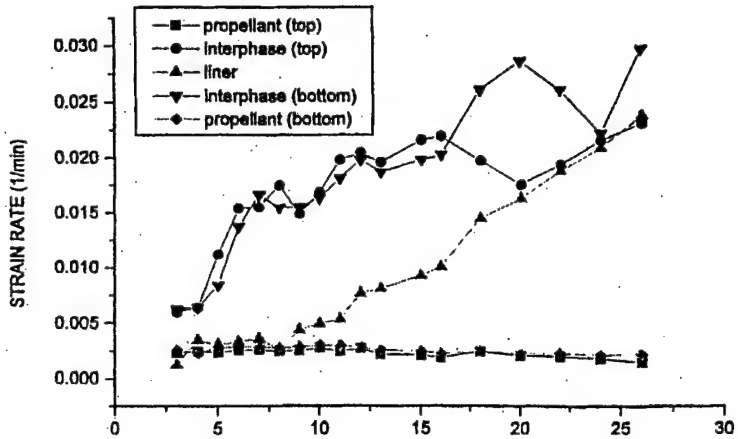
12

13

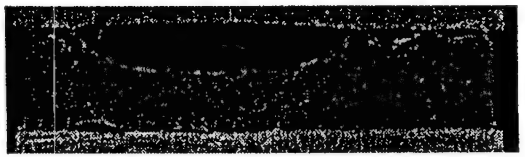
The Strain Rate in the Thin Liner Layer of the Propellant/Liner/Propellant Specimen Increases With Increasing Time

- The average strain rate in the liner layer increases and that in the propellant layer decreases while the load increases.
- There are interphase regions near the interfaces. Before major cracks appear, the strain rates in the interphase regions are significant higher than that in the liner and propellant layers.

Pls add the "ly" to "significant" (should read as "significantly")



The strain rates of different regions



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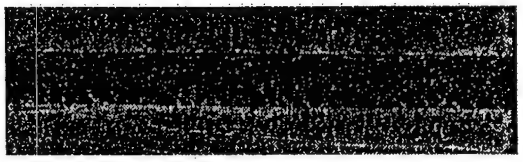

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Conclusions

- The developed technique can be used to predict the crack size in high stress regions with good accuracy.
- Under confined pressure, cracks grow slowly.
- Based on a linear cumulative theory and x-ray data, the critical damage condition is independent of load history.
- The computed tomography technique is a promising technique to monitor damage processes inside the specimen.
- The strain rates in the interphase regions and in the liner are significantly higher than those in the propellant, and they vary with time.

Slide 1-7 Self-Explanatory

Slide #8 We included the pressure effect in a constitutive model, which was incorporated in a computer program.

The dark areas, shown in the top picture, are the end-taps of the analogy specimen.

The two crack initiation locations, shown in the center picture , are consistent with the high stress locations determined from the finite element analysis.

Slide #9 During crack turning, a three-dimensional stress state exists along the crack front and the stress distribution is non-uniform. Under this condition, the crack will grow slowly. After the crack turning process is completed, the shear stress (Mode II Stress) ~~does~~ no longer exist and the crack grows under normal stress (Mode I).

pls delete "does"

pls add an "s" to "exist"

The point G shown in the left side of the top picture indicates the crack tip location after the completion of the crack turning process, whereas the point G shown in the right side of the top picture indicates the crack tip location during the crack turning process.

delete these 2 commas

delete these 2 commas

The two bottom pictures show the fringe patterns determined from the pohotoelastic analysis. The picture to the left shows that the fringe pattern is symmetric with respect to the tip of the completed turned crack, indicating there is no shear stress. The picture to the right shows that the fringe pattern is rotated with respect to the tip of a turning crack, indicating there is shear stress.

Pls add a period

Slide #10 For a given time, the values of the damage parameter depend on time. However, the value of the critical, or the maximum, damage parameter is independent of time, or loading history.

The different colors shown in the figure indicate different transmitted x-ray intensities, which are related to the damage in the material. For pre-damaged specimen, prior to testing, the specimen was stretched to 20% of strain to induce damage in the specimen. The similarity between the two x-ray pictures implies that the effect of load history on the critical damage characteristics is not significant. For a solid propellant, a 9.5% difference in the critical x-ray intensities, 1828 and 2019, is insignificant.

Slide #11 The representative volume is defined as a volume in which the macrostructure, or the material property, is the same as a large specimen such as JANNAF dogbone specimen.

pls add "the" where indicated — the

The black spots, shown in the CT Image, are the low-density regions in the center plane of the specimen.

The RMS (root mean square) values of the supervoxel means are used to estimate how the material varies from supervoxel to supervoxel. The curve starts to level off around 2 mm, indicating the material, or the microstructure, does not vary with supervoxel size. The drop of the RMS value at 5 mm is due to a large step used in data analysis. — pls delete this period — pls add a period here

Slide #12 Based on my probabilistic crack growth model, crack growth rate decreases as the damage gradient is increased. Since the damage gradient is commeasured with the strain gradient, the increase in strain gradient under 1000 psi confined pressure will induce a slow crack growth (Bottom Picture).

This word does not exist in the dictionary - is it a new scientific term or do you mean "correlated?" —

Under 1000 psi confined pressure, the crack grows slowly beyond the maximum applied load (Top Picture).

Slide # 13 Based on test results, we found that the strain rates in the liner and the interface regions are different from the applied strain rate and they increase with increasing time (Top Picture). This phenomenon has not been reported in the rocket industry and research community.

At 33 min 40 sec a large crack initiates in the center of the upper interface between the propellant and the liner (Bottom Picture).

Slide #14 Self-Explanatory